RC1: 'Comment on hess-2023-236', Anonymous Referee #1, 15 Feb 2024:

General comment

Dear authors,

The paper introduced a novel approach for combining a technical assessment and a cost benefit analysis for decisions on water supply solutions on an island. The cba is divided into a financial cba and an extended cba demonstrating the importance of accounting more than pure project internal financial consequences in decisions. The extended cba provides examples on how ecosystem services such as carbon sequestration can be monetized and thus included in a cba. The paper delivers an important and not widely covered topic of combining technical assessments into economic evaluation including monetizing effects on ecosystem services. The paper contributes to the state-of-the-art provided some amendments suggested below.

REPLY: We would like to thank you for your time and work to review our manuscript. We are happy you found the work contributes to the state-of-the-art of combining technical assessments into economic evaluation including monetizing effects on ecosystem services. Please find below our answers to the specific comments.

Specific comments

Row 83: The authors state, with references, that the CBA method falls short to adequately monetarize ecosystems services. I would prefer it if this was described with more details, thus, in what way does it falls short and why?

REPLY:

We have extended the text in the manuscript as follows (changes/additions marked yellow):

"CBA analysis has been applied in existing literature to assess the economic feasibility of MAR projects (e.g., Halytsia et al., 2022; Rupérez-Moreno et al., 2017) but has not included ecosystem services (ES): one of the highlighted benefits of NBS. Furthermore, the CBA method falls short to adequately monetarize ecosystems services (e.g., Maliva, 2014; Ruangpan et al., 2020; Network Nature, 2022; Sudmeier-Rieux et al., 2021; Wegner and Pascual, 2011). In fact, by definition a CBA should be able to consider all benefits and costs of a measure by translating social, environmental and economic aspects into monetary values (Clinch, 2004; Hanley, 2013). Often, however, only partial benefits of a measure are included in a CBA, especially marketed values (Clinch, 2004), thereby neglecting ethical and cultural aspects (Vojinovic et al., 2017), and implicitly setting all neglected benefits to zero (Dominati et al., 2014). Therefore, we propose a methodology in this study that sets itself apart from already published research as it aims to combine a technical feasibility assessment and use the results to assess them in an extended cost-benefit analysis (CBA) with ecosystem services analysis. Ecosystem services are modelled with the InVEST software (Sharp et al., 2020)."

Additional references:

Clinch, J. (2004). Cost–benefit analysis applied to energy. In C. J. Cleveland (Ed.), Encyclopedia of energy (pp. 715–725). Elsevier Acad. Press. https://doi.org/10.1016/B0-12-176480-X/00237-0

Dominati, E. J., Robinson, D. A., Marchant, S. C., Bristow, K. L., & Mackay, A. D. (2014). Natural capital, ecological infrastructure, and ecosystem services in agroecosystems. In Encyclopedia of agriculture and food systems (pp. 245–264). Elsevier. https://doi.org/10.1016/B978-0-444-52512-3.00243-6

Hanley, N. (2013). Environmental cost–benefit analysis. In Encyclopedia of energy, natural resource, and environmental economics (pp. 17–24). Elsevier. https://doi.org/10.1016/B978-0-12-375067-9.00103-0

Vojinovic, Z., Keerakamolchai, W., Weesakul, S., Pudar, R., Medina, N., & Alves, A. (2017). Combining ecosystem services with cost-benefit analysis for selection of green and grey infrastructure for flood protection in a cultural setting. Environments, 4 (1), 3. https://doi.org/10.3390/environments4010003

Row 91: Is it reasonable to say that the aim of the result is to show financial benefits of NBS? It sounds a bit biased. Maybe it would be better to say that the result from the CBA aims at providing a systematic review of different measure alternatives where NBS is one that is compared to more traditional ones? Thus, the result should speak for itself; the aim should not be to get a certain result.

REPLY: We agree with this suggestion, we have reformulated the paragraph as follows: ”Results aim to allow a systematic comparison of NBC and RO costs and benefits to policy and decision makers and help justify their implementation.”

Also, I think the aim could benefit from having a few objectives as well specifying more directly what has been carried out in the study…. E.g., 1) developing the technical assessment of MAR on tropical islands, 2) developing the methodology for extended cba with ES-analysis, 3) demonstrating the method on a case study etc…

REPLY: We agree with the suggestion and have adapted the paragraph starting in row 88: ”In this work, (i) a technical assessment including risk assessment of MAR on small island nations is developed. Next, (ii), a methodology for an extended CBA with ES analysis is proposed. The methodology aims to explore the feasibility of NBS and RO from an economic and ecosystem services perspective. The two developed methodologies are then, (iii), applied to a study case on the island of Grand Bahama, The Bahamas. This study aims to show methods for investigating ecosystem services from an economic perspective. Results allow a systematic comparison of NBC and RO costs and benefits for, e.g., policy and decision makers and help justify their implementation.”

Row 170 and forward: The methodology is not sufficient enough. The criteria is not defined or explained. One table naming all the parameters / criteria used with an explanation on what data, what tools and what criteria value that were used for the evaluation needs to be explained. The MCDA is not explained in sufficient details eighter. Please rewrite this part and provide sufficient information on the methodology so that the reader of the text has the possibility to judge the method and understand the procedure.

REPLY: We have extended this section, to explain needed data, the parameters/criteria, the tools applied and the criteria for the values better. Nevertheless, we think a display in a table is not suitable. As for the risk assessment, for the suitable aquifer and for the selection of the MAR scheme, the criteria vary based on site specific information collected and decisions taken in the steps before. Nevertheless, we have added a table with a general overview of the methodology (see below). Therefore, the applied tools and needed data base can only be narrowed down after following different selection steps (explained in the results section). For example, a review paper by Sallwey et al. (2019) has attempted to describe the summarized criteria used for the selection of suitable MAR locations. Another example is the review paper by Imig et al. (2022), where the authors summarize decision criteria and different methods used for risk assessment of MAR sites based on data availability. Therefore, we have restricted the methodology description to the site-specific information in Grand Bahama and added explanation about data, and decision criteria in the result section. We propose to extend section 2.4 as follows, after line 155:

"As the first step, the **(i) water demand** is defined, as without water demand a MAR scheme is not needed. The demand can either be defined based on technical guidelines from the country's legislation or based on the documented water use of the consumers. It is reasonable to predict a water demand for the design life of the MAR measure, e.g., commonly 30 years are set in water supply infrastructure. We collected data from the water authorities in Grand Bahama to calculate the water demand. For the **(ii) identification of suitable aquifers,** the hydrogeological properties of regional aquifers were collected. Hydrogeological properties should include the lithology and the location of the aquifer, storage capacity, and hydraulic conductivity (DEEPWATER-CE, 2020a; NRMMC, 2006). Based on the available data and the site-specific information, a suitable aquifer with sufficient storage capacity to supply the water demand shall be chosen. After defining the water demand and a suitable aquifer, the **(iii) water source(s) for groundwater recharge** should be identified, e.g., rainwater, surface water, or desalinated water. Based on the available water source, a **(iv) suitable MAR scheme** can be selected for the water demand and the available aquifers. This is necessary as, e.g., rainwater harvesting schemes have different requirements regarding groundwater levels compared to a riverbank filtration scheme (Sallwey et al., 2019). Specific criteria and data needed for their identification were determined in a literature review. They are not further summarized here but specified for the chosen MAR type in the results section. For step **(v),** we conducted a qualitative **risk assessment** with a risk score matrix after Swierc et al. (2005). Potential hazards for a MAR scheme in Grand Bahama for the risk assessment were chosen from a collection published in a review paper by Imig et al. (2022). For step **(vi) selection of suitable location,** we developed selection criteria based on information gained from the previous steps. Similar to step (iv), the selection criteria and the data we refrained from further specification in the methodology section for all possible MAR types due their quantity. The criteria for the chosen MAR scheme (in step (iv)) are summarized in the results section based on information from DEEPWATER-CE (2020a), CEHI et al. (2010), and NRMMC (2006). The criteria were assessed using the geographical information system QGIS

(2020) and were used in a multi-criteria decision analysis (MCDA) (Sallwey et al., 2019). The achievable recharge volume from the rainwater harvesting scheme was calculated based on recommendations by the German institute for norms (DIN, 2002), where details are given in Section S1 in the Supporting Information (SI). If the steps (i)-(iii) and (v) generate a negative evaluation, we suggest extending the study area or stopping the investigation. Otherwise, if all steps can be followed and result in a positive evaluation, MAR is considered to be feasible for the study site. Input data used to conduct the technical feasibility assessment (and the other parts of the holistic analysis) are described in Table S1 of the SI."

Publications mentioned in this reply:

Sallwey, J., Bonilla Valverde, J.P., Vásquez López, F., Junghanns, R., Stefan, C., 2019. Suitability maps for managed aquifer recharge: A review of multi-criteria decision analysis studies. Environ. Rev. 27, 138–150. https://doi.org/10.1139/er-2018-0069

Imig, A., Szabó, Z., Halytsia, O., Vrachioli, M., Kleinert, V., & Rein, A. (2022). A review on risk assessment in managed aquifer recharge. *Integrated Environmental Assessment and Management*, *18*(6), 1513–1529.

Row 195: I would like to have a comment of the chosen project time/ life time of the project. 30 years seems a bit short for a large project as a drinking water supply solution.

REPLY: We agree that the timeframe seems short, and maybe even not sustainable as drinking water will be needed also after that period. The timeframe of thirty years was chosen after communication with engineer offices such as Phoenix Engineer and personal experiences from prior work in the water supply infrastructure sector. Most water infrastructure projects are funded by governmental institutions and are influenced by current politics and public opinion. We think it lies in the nature of the funding sources that the projects are not planned for a longer period as the current government will not benefit from their effect if they have to calculate expenses extending over their legislative period.

Section 2.4-2.5: In general, it is difficult to follow the procedures and what effects that are included in what CBA. as it is now, the reader must go back to the main text in the methodology in order to be able to interpret the result shown in the CBA-tables. This makes interpretating the result difficult and time consuming. I suggest a table that clarifies the differences between the three analyses in a structured way where a summary on what parameters are included in e.g., the financial cba compared to the extended cba for both the RO, RRWH, and reforestation.

REPLY: We agree that the methodology could be complicated to understand at a first glance, and we thank you for the suggestion on adding a schematization of the methodology through a table. We have added the following table in the methodology, for better understanding, while reviewing the results.

Factors	Technical feasibility	Financial CBA	Extended CBA	Analyzed measure
Water demand	✓			MAR types (incl. RRWH)

Aquifer type	✓			MAR types (incl. RRWH)
Water source for MAR	✓			MAR types (incl. RRWH)
MAR technique	✓			MAR types (incl. RRWH)
Risk assessment	✓			MAR types (incl. RRWH)
Location	✓		✓	MAR types (incl. RRWH)
Measure’s costs (C)		✓	✓	RRWH, RO, reforestation
Benefits of the drinking water supply (DWS)		✓	✓	RRWH, RO, reforestation
ES of carbon sequestration (Carbon)			✓	RRWH, RO, reforestation
ES of timber provisioning (TP)			✓	RRWH, RO, reforestation
ES of habitat provisioning (HP)			✓	RRWH, RO, reforestation
ES of tourism (T)			✓	RRWH, RO, reforestation

Discussion/summary/conclusions: I think the discussion of the result could benefit greatly by including a thorough discussion about the uncertainties associated with the analysis. With uncertainties I mean:

- Are the parameter values, thus the numbers used in the CBA certain or could the costs and benefits differ?
- Are the models used to determine the values of the different cost and benefit items in the CBA certain, or could other models/other ways of valuating effect have an impact on the value of the cost-benefit item and thus the overall result?
- Are there effects that have not been included in the extended cba that could have had an impact on the overall result?

REPLY: Thank you very much for outlining these topics. Please see our reply below, to a question on uncertainty raised by the second reviewer.

Technical comments

Row 113 and 115: You do not have to refer to figure 1 once again.

REPLY: We have removed the references to Figure 1.

Row 152: figure 3?

REPLY: We have moved the initial reference of Figure 3 from line 157 to line 152.

Figure 3 could be moved closer to section 2.4 where it is referenced.

REPLY: We have moved Figure 3 to the end of section 2.4.

Result section: Wouldn't it be better to have the result tables located closer to the text describing the results?

REPLY: We have added the extensive results tables to the Appendix to allow the reader to not be interrupted in the reading flow by the tables. We will contact the layouting team of HESS to discuss possibilities to display the tables in a published version and evaluate their location again.

RC2: 'Comment on hess-2023-236', Anonymous Referee #2, 16 Apr 2024

The study provides a comprehensive analysis of the aftermath of Hurricane Dorian's impact on Grand Bahama Island, specifically addressing the extensive flooding and saltwater intrusion into aquifers, which significantly affected the island's water supply. Through an exploration of Managed Aquifer Recharge (MAR) and reforestation as potential nature-based solutions, the study conducts a thorough technical assessment of MAR, identifying plausible implementation sites. Additionally, it offers insightful financial and cost-benefit analyses, integrating ecosystem services, for both MAR and reforestation strategies.

The study's approach is noteworthy for its emphasis on holistic consideration and sustainability. While not exhaustive, it offers relevant implications for addressing urgent environmental challenges and enhancing the resilience of ecosystems and local communities in Grand Bahama. However, the study would benefit from further clarification and organization of the methodology. Additionally, a more thorough analysis of the results concerning uncertainty is warranted, considering that the findings were derived from limited data.

REPLY: We thank the reviewer for his/her time and the feedback to our proposed manuscript. We have adjusted the organization of the methodology section 2.4 and extended the description after line 155: please see above in our reply to the first reviewer.

Additionally, a more thorough analysis of the results concerning uncertainty is warranted, considering that the findings were derived from limited data.

REPLY: Thank you for raising this point. In response to that, and to points on uncertainty raised above by the first reviewer, we will extend the discussion in the manuscript as follows (after line 394):

To take uncertainty into account in our analyses, we first applied multiple discount rates. In fact, based on past research, discount rate is amongst the most sensitive parameters and is hence an important source of uncertainty (Costanza & Daly, 1992). A low discount rate reduces the devaluation of future effects, favoring policies with long-term benefits and low present costs, while a high discount rate does the opposite (Dominati et al., 2014; Hanley, 2013). Thus, a low rate values long-term benefits more, whereas a high rate emphasizes short-term benefits (Dominati et al., 2014). This approach allowed us to understand the effects of one of the most relevant uncertainty sources on the results.

However, other sources of uncertainty can be found in our ES assessment and evaluation. First, uncertainty is inherent in all techniques used for ES estimations (Dominati et al., 2014). Costanza et al. (2017) note that imperfect information affects the evaluation of ES, beginning at the process understanding level and extending through the quantification and economic valuation of ES (Dominati et al., 2014). This imperfection stems from limited biophysical and economic data availability (Dominati et al., 2014) or from relying on simplistic assumptions or expert opinion, such as the relationship between land cover, water provision, and land use (Vollmer et al., 2022). Also, the way this imperfection is included in the ES estimations depends on which models and software are chosen. Due to time resources, our analysis used one main software (InVEST) to guide the ES estimations, but others exist. For example, a promising alternative model is the ARtificial Intelligence for Environment & Sustainability approach (ARIES) (Villa et al., 2014). In our study, multiple parameters were chosen deterministically due to data scarcity (e.g., to estimate investments costs or operation costs), and might be adapted in the future to address uncertainty.

Second, the lack of standards for ES modeling, assessment, and valuation, along with the high time and resource demands of sophisticated methods, pose some challenges (Costanza et al., 2017). For example, this can lead to double counting, where provisioning, regulating, or cultural services are counted alongside their supporting services (Costanza et al., 2017). Inappropriate classification often causes this issue (Fisher et al., 2008). In our analysis, we made sure that double counting is not happening.

In terms of challenges related to the inclusion of the ES assessments into an extended CBA, uncertainties include determining when and how to monetize the benefits of a measure (European Centre for River Restoration, 2022), the lack of result validation (Sudmeier-Rieux et al., 2021), and the exclusion of parameters or ES that cannot be expressed in monetary terms (Ruangpan et al., 2020). For example, in our analysis, we were not able to include the spiritual significance of forest areas in Grand Bahama. Potential ways to address these sources of uncertainty in the future are to use the Monte Carlo approach, or simpler methods such as assuming a spatially uniform error or using alternative raster inputs (Hamel & Bryant, 2017; Vining & Weimer, 2010). Additionally, using multiple models to simulate the same process could help assess the effects of conceptual model uncertainty (Hamel & Bryant, 2017).

Additional references:

Costanza, R., & Daly, H. E. (1992). Natural capital and sustainable development. Conservation Biology, 6 (1), 37–46. https://doi.org/10.2307/2385849

Dominati, E. J., Robinson, D. A., Marchant, S. C., Bristow, K. L., & Mackay, A. D. (2014). Natural capital, ecological infrastructure, and ecosystem services in agroecosystems. In

Encyclopedia of agriculture and food systems (pp. 245–264). Elsevier. https://doi.org/10.1016/B978-0-444-52512-3.00243-6

European Centre for River Restoration. (2022). The economics of river restoration. Retrieved June 2, 2022, from https://www.ecrr.org/River-Restoration/Economics

Fisher, B., Turner, K., Zylstra, M., Brouwer, R., de Groot, R., Farber, S., Ferraro, P., Green, R., Hadley, D., Harlow, J., Jefferiss, P., Kirkby, C., Morling, P., Mowatt, S., Naidoo, R., Paavola, J., Strassburg, B., Yu, D., & Balmford, A. (2008). Ecosystem services and economic theory: Integration for policy-relevant research. Ecological Applications, 18 (8), 2050–2067. http://www.jstor.org/stable/27645921

Hamel, P., & Bryant, B. P. (2017). Uncertainty assessment in ecosystem services analyses: Seven challenges and practical responses. Ecosystem Services, 24, 1–15. https://doi.org/10.1016/j.ecoser.2016.12.008

Villa, F., Bagstad, K. J., Voigt, B., Johnson, G. W., Portela, R., Honzák, M., & Batker, D. (2014). A methodology for adaptable and robust ecosystem services assessment. PloS one, 9 (3), e91001. https://doi.org/10.1371/journal.pone.0091001

Vining, A., & Weimer, D. L. (2010). An assessment of important issues concerning the application of benefit-cost analysis to social policy. Journal of Benefit-Cost Analysis, 1 (1), 1–40. https://doi.org/10.2202/2152-2812.1013

Vollmer, D., Burkhard, K., Adem Esmail, B., Guerrero, P., & Nagabhatla, N. (2022). Incorporating ecosystem services into water resources management-tools, policies, promising pathways. Environmental management, 69 (4), 627–635. https://doi.org/10.1007/s00267-022-01640-9